REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-98-

0632

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
July 15, 1998

3. REPORT TYPE AND DATES COVERED
Final Report-1 Jun 95 - 31 May 98

4. TITLE AND SUBTITLE
Development and implementation of a towering cumuli & transient cumulonimbi parameterization using large eddy simulations of deep convection

5. FUNDING NUMBERS
Grant (G):
F49620-95-1-0386

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Final Report

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

In support of the overall goal of this research to develop a worldwide, interactive nested-grid cloud forecasting numerical prediction model, a new cumulus parameterization scheme and a new two-stream radiation scheme has been developed.

The cumulus parameterization scheme is flexible enough to be used at virtually any model grid spacing and is especially useful in an interactive nested grid model where grid spacings from about 100 km to a few kilometers may be employed at the same time over different parts of the model domain.

A new two-stream radiation scheme has been developed. The scheme interacts explicitly with the microphysics of the model including the both a bin-representation of liquid and ice particle size-spectra and multi-phase bulk microphysics models with specified size-spectra. The scheme includes a coupling between radiation and the vapor-deposition/evaporation of hydrometeors. The radiation model coupled to a cloud-resolving model of Arctic stratus clouds has been used to examine radiative influences on summertime and transition-season Arctic stratus.

14. SUBJECT TERMS
Cloud parameterization; Cloud radiation; Cloud prediction

15. NUMBER OF PAGES
8 pages

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

Final Technical Report

for project entitled:

Development and Implementation of a Towering Cumuli & Transient Cumulonimbi Parameterization using Large Eddy Simulations of Deep Convection

Grant No. F49620-95-1-0386

To:

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Contents

1 Introduction

This is the final technical report for Grant No. F49620-95-1-0386 for the period 1 Jun 95 - 31 May 98. The report includes a summary of research progress and an identification of technical transitions which are taking place.

2 Objectives

The objectives are to develop convective and radiation parameterizations to support our research on worldwide cloud prediction. The convective parameterization is designed to be used in nested-grid models having a broad range of grid spacings. The radiation scheme, in turn, is designed to interface with the microphysics and cloud parameterization schemes directly, and to accurately calculate the radiative effects of cumulus clouds, boundary layer clouds, cirrus, and even Arctic stratus clouds.

3 Status of Effort

The primary goal of developing a deep cumulus parameterization suitable for use in mesoscale models was completed by Scot Rafkin (1996). The parameterization is now currently being tested by other researchers over a wide variety of convective situations. Preliminary indications during this testing phase are quite encouraging. The new convective parameterization has now gone through the second generation stage of development in which the scheme is optimized and streamlined for use in the realtime forecasting parallel version of the Regional Atmospheric Modeling System (RAMS), Version 4.2.

The radiative transfer model of Harrington (1997) has been completely coupled to the liquid and ice-phase microphysical models in use within the RAMS framework. This includes the coupling of radiative heating and cooling to the vapor deposition growth equation of water drops in the bin microphysical framework of Feingold et al. (1988).

Studies of summertime and transition-season (fall and spring) Arctic stratus have elucidated the couplings between microphysical and radiative processes within these cloud systems. The maintenance of autumnal mixed-phase Arctic stratus has been explored along with a new mechanism for the layering of liquid Arctic stratus. The explicit coupling of the radiative transfer model to the liquid bin microphysical model has allowed the study of radiative transfer effects on the vapor growth of droplets.

4 Accomplishments and New Findings

4.1 The cumulus parameterization scheme

As stated above, the development of a deep cumulus parameterization suitable for use in mesoscale models is complete. The parameterization is a significant advancement in the field for several reasons. First, it is flexible enough to be used at virtually any grid spacing. This frees the modeler from having to arbitrarily decided when to switch from a "large-scale" to a "mesoscale" parameterization. This is particularly important when nested grids are involved. Additionally, a new paradigm for convective parameterization is introduced. This has the benefit of potentially stimulating new research into parameterization at the

mesoscale, and also provides a new framework from which parameterizations can be modified and improved. Finally, the scheme has been designed to interface with a new parameterization of the mesosscale stratiform anvil clouds of mesoscale convective systems (Alexander and Cotton, 1998).

In regards to specific Air Force missions and potential applications to Air Force and civilian technology challenges, the parameterization will have an impact in any numerical weather prediction model ranging from those with grid spacings on the mesoscale to general circulation models. It will be particularly useful to cloud-forecasting models. A global, interactive-nested grid version of RAMS has been constructed to serve as a prototype test bed for such applications. Unfortunately, continuation funding was not provided to allow the testing of this new cloud forecasting approach.

4.2 Radiation model couplings to microphysics

The two-stream radiative transfer model, developed by Harrington (1997), has been completely coupled to the RAMS model including all existing microphysical parameterizations. Coupling to the bulk microphysical model of Walko et al. (1995), in which gamma size distributions are assumed for all hydrometeors, is accomplished by deriving optical properties for all radiation bands using Mitchell's (1997) approach for water drops and Mitchell and Arnott's (1994) approach for ice crystals. As the bin microphysical models of Feingold et al. (1988), for water drops, and Reisin et al. (1996), for ice particles, allows for the variation of concentration and mass within 25 to 32 discrete bins, a method has been developed which allows for the accurate computation of the optical properties for the distributions as a whole from the individual bin information. Such a method responds accurately to alterations in distribution shape without having to make any *a priori* assumptions.

Since the optical properties are derived for each bin of the microphysical models, this information may be exploited in order to discover how radiative transfer processes affect the growth of hydrometeors. Building on the work of Austin et al. (1995), a method has been developed for incorporating the radiative terms into the condensational growth equations for water drops in the bin microphysical framework (Harrington, 1997). This method has been tested and shown to be accurate within the limits of the model computational domain.

4.2.1 Simulation of summertime Arctic stratus

The coupled bin microphysical and radiative transfer models has been used in studies of summertime Arctic stratus clouds (ASC). These clouds tend to have a wider development regimes than the traditionally examined marine stratocumulus. Arctic stratus are a persistent feature of the summertime Arctic basin and may exist as single layer or multi-layered features. Their local environment may be strongly mixed, which is similar to marine stratocumulus except that surface fluxes do not contribute significantly to the cloud layer, or they may exist in a stable environment which appears to be favored by multi-layered systems (Curry et al., 1988).

The coupled radiative and microphysical models were used to study interactions between these processes for the June 28, 1980 case discussed by Curry et al. (1988). This case was selected because it produces a strong mixed-layer through cloud-top radiative cooling which generates buoyancy, thus being an excellent vehicle for microphysical/radiative experiments.

Simulation results for a set of control cases produced good agreement between the model and Curry et al. (1988) and Curry (1986) observational results. Model liquid water contents (LWC) had cloud top maxima of about 0.48 $g\ m^{-3}$ with a linear with height decrease to cloud base (similar to that shown by Curry, 1986). Cloud top infrared cooling rates (-6.5 $K\ h^{-1}$) and solar heating rates (0.7 $K\ h^{-1}$) were quite similar to those presented in Curry (1986). Turbulent fluxes of momentum and water species all compared well with Curry (1986) diagnoses from observations.

Sensitivity studies were run to examine the effects that cloud condensation nuclei (CCN), drizzle, shortwave heating and optical property parameterizations have on the dynamics of the cloud layer. It was found that CCN concentrations have a mitigating effect on circulation strength through drop concentration and drop distribution breadth. Simulations show that circulation strength and depth are greater for smaller drop (CCN) concentrations if the drop size distributions in the cloud are broad. For narrow drop distribution functions, this characteristic is reversed and larger drop (CCN) concentrations tend to have stronger circulation strengths. This dependence appears to be strongly linked to the interaction of the microphysics with radiation at cloud top. In the case of the narrow distribution functions, large concentrations produce more longwave cooling within the mixed-layer (as opposed to the overlying inversion layer) and, therefore, may readily generate convection.

Drizzle processes reduce circulation strengths within the ASC layer and appears to be due to the effects of two processes. First, and foremost, without the effects of drizzle large drops are not produced and, thus, absorption of solar radiation is reduced and reflection increased in the no drizzle simulations. The increased longwave cooling at cloud top produces larger positive buoyancy fluxes and, thus, stronger circulations. That shortwave radiation mitigates the strength (and depth) of the circulations was quantified by studying simulations in which only longwave radiation was utilized. These simulations produced much stronger and deeper circulations than those which included shortwave radiation, thus showing that shortwave radiation constrains the strength and depths of the eddies. Simulations in which optical properties were allowed to respond to the bin microphysical representation showed the importance of accurate cloud-radiative interactions. Simulations which used simple gamma distribution derived optical properties produced microphysical and dynamical structures that were significantly different from those produced with the accurate cloud-radiation interactions. The accurate optical property interactions produced clouds with larger cloud-base drizzle rates, larger cloud top distribution breadths, and eddies that were both stronger and deeper than those with the simple optical property representation. These studies illustrate the importance that radiative-microphysical couplings can have in simulating ASC decks.

4.2.2 Radiative influence on cloud droplet growth

Previous numerical experiments that include the effects of radiative transfer on cloud drop growth have either focused on idealized drops or distributions of drops growing at cloud top (e.g Austin et al., 1995; Roach, 1975) or on overall effects in detailed models with little discussion of the radiative-drop growth effects (e.g. Ackermann et al., 1995; Bott et al., 1990). Thus, we designed a set of experiments to bridge the gap between the idealized studies and full predictive modeling studies including the effects of shortwave radiation which has been neglected in the majority of such studies. Our approach centers on using the trajectory parcel model (TPM) of Stevens et al. (1996) modified so that radiative information is included. The input data for the TPM is produced by placing any number (in this case 500) of point

parcels distributed throughout the cloud domain and, during the coarse of the simulation thermodynamic, dynamic and radiative information is stored.

As one would expect, enhancement of droplet growth through longwave cooling to space is highly dependent upon cloud-top residence time. Trajectory model results show that the cloud-top residence time required to initiate drizzle is reduced substantially by including the radiative term in the drop growth equation (from 40 minutes to 20 minutes for a simulation with 100 cm^{-3} CCN concentration). This result is also highly dependent upon the CCN concentration used in the simulation. Higher CCN concentration simulations illustrate that much more time at cloud top is required for the initiation of drizzle, almost 50 minutes for 500 cm^{-3} CCN concentrations. The number of parcels with large cloud-top residence times is quite small, thus the enhancement of drop growth by radiative cooling in large CCN concentration simulations is dominated by only a few parcels. Because of this, drizzle effects are not largely enhanced by radiative effects in clouds with numerous CCN.

Since emission in the infrared increases with drop size through increases in the surface area and Lorenz-Mie absorption coefficient (Q_{abs}), large drops may exist in environments that are classically considered to be subsaturated. Parcels with long cloud-top residence times (greater than about 20 minutes) can produce slightly subsaturated environments through the growth of drops with radii greater than about 15 microns. In such an environment, smaller cloud droplets can readily evaporate while larger drops continue to grow, therefore producing a bi-modal cloud top drop spectra. Since few parcels have large enough cloud-top residence times to produce this bimodality, the average effect is a broader overall drop spectrum at cloud top.

Simulations which include the radiative effect in the RAMS simulation of ASC show that, for low CCN concentrations (100 cm^{-3}), drizzle-sized drops are produced at cloud base between 0.5 and 1 hour earlier than in simulations that do not include the radiative term in drop growth. The microphysical structure of the radiation and no-radiation simulations are similar with the no-radiation fields showing a time-lag as compared the the simulation with radiation. Simulations which utilize higher CCN concentrations (500 cm^{-3}) show little difference between the radiation and no-radiation simulations, therefore corroborating the results of the TPM simulation. Thus, radiative effects on the growth of cloud droplets appears to simply decrease the time of drizzle onset while having little effect on the overall cloud structure. Clouds with high CCN concentrations, which produce little drizzle anyway, are not likely to drizzle with the inclusion of the radiative term. It appears that radiative effects may be most important for clouds which are on the verge of producing drizzle.

4.2.3 Transition-season simulations of ASC

During the fall and spring (transition-seasons) in the Arctic basin low cloud fraction and type undergo a rapid transition. The persistent, liquid summertime ASC are replaced by mixed-phase clouds in the fall and mixed-phase/ice clouds in the winter with clear-sky ice crystal precipitation apparently being the dominate low-cloud type during winter (Curry et al., 1996). The nature of the transition in low cloud type and fraction that occurs during the fall and spring have not been examined in detail as little data exists for these periods. Recently, interest in the transition and winter seasons has increased due to studies that show that the Arctic region may be particularly susceptible to climatic perturbations (Walsh and Crane, 1992). We explore the possibility that these changes in cloud type and fraction are microphysically forced along with possible mechanisms behind persistent mixed-phase clouds in

autumn (which are unstable because of the presence of the ice phase). This is accomplished by cooling the summertime sounding used in the above ASC simulations. The initialized sounding is cooled in increments of $5C$ and $10C$, while relative humidity is kept constant. Simulations over an 8 hour time period are conducted using the mixed-phase bin microphysical model of Reisin et al. (1996) for both coolings (control simulations). Sensitivities are conducted around each simulation which allow the exploration of ice microphysical processes on the cloud systems. Recently, Pinto (1998) has examined two autumnal mixed-phase cloud systems, one which shows a deep mixed-layer and characteristics that are similar to those produced by our simulations.

The control simulations produce ice slowly over the first four hours of the simulation time and, as ice contents increase, rapid conversion of liquid water to ice occurs during the 4 to 5 hour period of the simulations. The simulation with lesser cooling ($5C$) rapidly looses liquid water to ice, however, it is able to remain stable over the coarse of the 8 hour simulation. The simulation which is cooled more ($10C$) glaciates rapidly over the 4 to 5 hour period and, eventually the liquid cloud collapses as it is converted to precipitating ice. Large liquid to ice conversion rates at colder cloud temperatures have been observed by Pinto (1998) in one of two mixed-phase clouds observed during autumn over the Beaufort sea. The stable simulation ($5C$) shows that a self-maintaining mixed-phase cloud may persist without the influences of large scale moisture advection. The ice phase affects the liquid layer by mitigating the liquid water content (LWC) produced within the cloud, the cloud drop concentrations and, therefore, the radiative cooling that occurs within the vicinity of cloud top. The precipitating ice crystals affect the lower portions of the boundary layer as cooling and moistening tends to stabilize these regions. The colder cloud situation ($10C$ cooled) shows that, if glaciation of the liquid cloud is rapid enough, the boundary layer may completely collapse and, thus, the maintenance of clouds in such regimes may require strong synoptic forcing.

Sensitivity studies show that the maintenance of the mixed-phase layers are strongly dependent upon ice crystal concentrations, ice crystal precipitation rates and on ice crystal habit. The production of a self-maintaining mixed-phase cloud appears to be confined to a narrow portion of ice concentration space (between 0.4 and 4 L^{-1}). Colder clouds are much more susceptible to ice concentration increases as liquid to ice conversion rates are more rapid.

Multi-layered cloud structures, a feature common of the Arctic boundary layer, can be produced through the cooling and moistening of the lower portions of the boundary layer by ice crystal precipitation. For this formation mechanism of multi-layered liquid clouds to operate, the upper liquid cloud must be reduced in thickness. This reduces the upper cloud optical thickness so that the lower, moistened layer may radiatively cool. This cooling of the lower layer allows for the production of water supersaturations and, thus, the activation of drops. The thin upper level cloud persists throughout the 8 hour duration of the simulation while the lower layer, formed after 5.5 hours, persists through the remainder of the simulation. Both upper and lower liquid cloud decks are maintained by cloud top radiative cooling.

5 Personnel Supported

Scot C.R. Rafkin, Graduate Research Assistant, Ph.D., 1996
Jerry Y. Harrington, Graduate Research Assistant, Ph.D., 1997

6 Publications

Cotton, William R., Robert Walko, Graham Feingold, Shuowen Yang, and Jerry Harrington, 1997: Mesoscale numerical prediction of clouds and cloud effects. WMO Workshop on Measurements of Cloud Properties for Forecasts of Weather, Air Quality and Climate, June 23-27, 1997, Mexico City, Mexico.

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7 Interactions and Transitions

The cumulus parameterization scheme is being used in prototype realtime forecasting of clouds, precipitation, and severe weather.

The radiation parameterization scheme, is being used by a number of researchers at CSU in simulations of fogs, tropical and mid-latitude convection, marine stratocumulus clouds, cirrus clouds, and in application studies at Mission Research Corporation.

8 New Discoveries, Inventions or Patent Disclosures

NONE

9 Honors/Awards

Dr. William Cotton is a Fellow of the American Meteorological Society and a Centennial Fellow of The Pennsylvania State University.

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